International Journal of Engineering and Management Sciences (IJEMS) Vol. 4. (2019). No. 1
DOI: 10.21791/IJEMS.2019.1.16.

Exhaust System Muffler Volume Optimization of Light Commercial passenger Car Using Transfer Matrix Method

B. MOHAMAD[1], K. JALICS[2], M. KERMANI[3]

[1]University of Miskolc, Faculty of Mechanical Engineering and Informatics, pywand@gmail.com
[2]University of Miskolc, Faculty of Mechanical Engineering and Informatics, machijk@uni-miskolc.hu
[3]University of Eastern Mediterranean, Faculty of Mechanical Engineering, mldkermani@gmail.com

Abstract. Nowadays, the automotive industry is focused on weight and size reduction. Main advantage of this weight and size reduction are improving the fuel economy. The specific fuel consumption of a vehicle can be improved through e.g. downsizing area of heat loss, if we focus on vehicle with weight reduction. Weight reduction can be done by replacing material or by changing the size (dimensions) of components. In the present work we have focused on Audi A6 muffler, troubleshooting and optimizing the muffler by changing pipe length of inlet and outlet, also by replacing the original mesh plate to porous pipe. Based on optimization, prototype has been built with the help of 3D design tool CATIA V5 and the calculations of transmission loss (TL) have been performed by MATLAB. Plane wave-based models such as the transfer matrix method (TMM) can offer fast initial prototype solutions for muffler designers. The principles of TMM for predicting the transmission loss of a muffler was used. Result of this present study of an existing muffler has been analysed and then compared with vehicle level test observation data. Noise level have been optimized for new muffler design. Other literatures were played significant rule for validate our results.

Introduction

The key functions of automotive engine exhaust system are transporting hot noxious exhaust gases from engine to atmosphere and significantly attenuating noise output from the engine through muffler, quickly and efficiently. The main objective of the muffler is reducing the noise level at the outlet and generate a suitable psycho acoustic perception of the exhaust noise. There are three types of mufflers available in market; Reflective (reactive) type, resistive (dissipative) type and hybrid muffler. In first type wave cancelation method is used to reduce the noise. This is used for low frequencies. In second type absorbing materials are used. The energy is converted into heat and then dissipated. This type is used for high frequencies. Third type is combination of reflective and absorptive. We can use hybrid muffler for all range of frequencies. Our test object is reflective type muffler. Exhaust gases are flowing not continuous, but in pulses. The commonly used four-cylinder engines have four distinct pulses per complete engine cycle. Fast moving pulse will create a low-pressure area behind it [1]. Many researchers have focused on muffler design and construction area. Researchers have published lot of papers on principles for muffler design. Wu et al [2] Used the Bulk-reacting porous materials as absorptive lining in packed silencers to reduce broadband noise. Modelling the entire silencer domain with a bulk-reacting material will inevitably involve two different acoustic media, air and the bulk reacting material. A so-called direct mixed-body boundary element method (BEM) has recently been developed to model the two-medium problem in a single-domain fashion. Yasuda et al [3] Present in their technical research, experimental study of acoustic intensity and the transient acoustic characteristics of its exhaust muffler were predicted using one dimensional computational fluid dynamics. The validation of the results of the simulation, were done to the transient acoustic characteristics of the exhaust muffler and measured in an anechoic chamber according to the Japanese Standard. It was found that the results of simulation were in good agreement with experimental results at the 2nd order of the engine rotational frequency. Mohamad et al [4] Used 1D AVL-Boost software to describe the effect of using different kind blend fuels on engine performance and exhaust properties. The result show variation of outlet temperature, and emission gas characteristics for CO, NOx, and CO2 by using different volume percentage of alcohol-gasoline blends. Mohamad et al [5] Studied the effect of Ethanol-Gasoline blend fuel on engine power output and emissions, the literatures results show great improvement in combustion process and exhaust gas characteristics. Mohamad et al [6] Presented in their technical paper review of muffler used in industry, and this review depicts flow and temperature distribution along the muffler ducts. The techniques for different methods used in the design, calculation and construction of muffler both experimentally, practically and transmission loss characteristics were described. 1D calculations are much faster, and still give a good overview of the system under investigation. Munjal et al. [7] analysed noise level of muffler. They used transfer matrix methodology and proposed expression-based model on the velocity ratio concept. They included the convective effects in the expression. The system matrix consistent with the boundary conditions from the geometrical model to evaluate the four-pole parameters of the entire muffler and thence its transmission loss, etc. Thus, the algorithm could be used in conjunction with the transfer matrix-based muffler programs to analyse the entire exhaust system of an automobile.

2. Methodology

2.1. CAD model

The geometry was implemented based on Audi A6 muffler prototype using CATIA V5 advanced design software, including inlet, outlet and chamber. The mesh plate was placed in the middle of the rectangular shaped chamber of the muffler. The cross section and the dimensions of muffler is explained in Figure 1.

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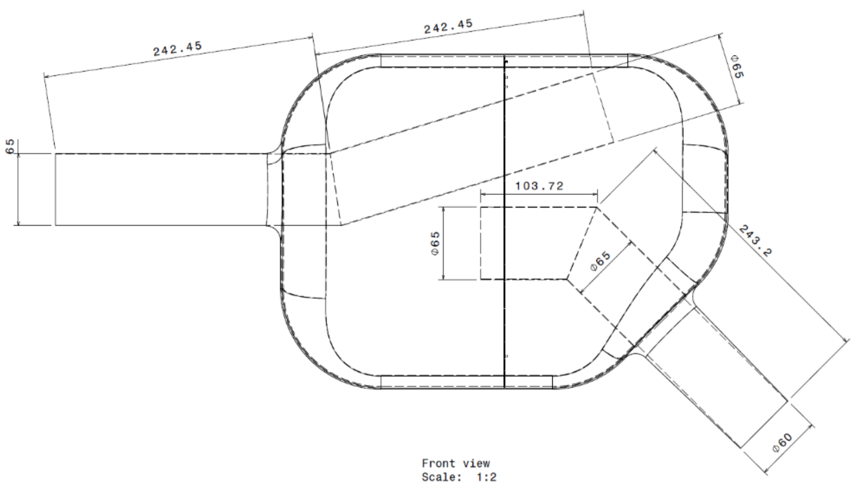

Figure 1. Muffler dimensions.

This modeling methodology is having 3D associativity in such a way that if we edit any dimension is the 2D sketcher, automatically muffler assembly will be updated. Based on flow properties results, problematic areas are identified, then input parameters of muffler like muffler length, minor and major diameter, number of holes in pipe and baffle position have been modified in CAD geometry. This methodology brings down the design time of muffler drastically.

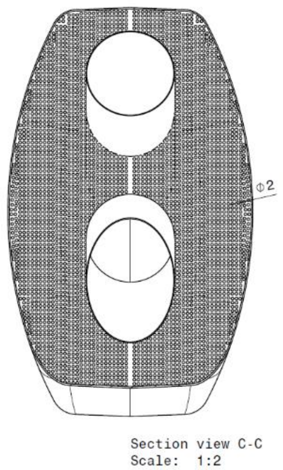

Figure 2. Internal construction of muffler (Mesh plate).

2.2. Transfer Matrix Method

The acoustical two-port system is usually expressed in the transfer matrix form with the acoustic pressure and volume velocity as variables. The transfer matrix method (TMM) is used for the determination of system parameters of a silencer element as a function of the element geometry, state variables of the medium, mean flow velocity, and properties of duct liners. The results presented below correspond to the linear sound propagation of a plane wave in the presence of a superimposed flow. In certain cases, the matrix may also be influenced by nonlinear effects, higher order modes, and temperature gradients; these latter effects, which can be included in special cases, are discussed qualitatively later in this section, but they are excluded from the analytical procedure described below. In this paper, the basic formulation of the Transfer Matrix Method (TMM) to predict the Transmission Loss of muffler elements has been summarized. Neglecting the impacts of higher order modes is the cause of validation of the plane wave propagation. Utilizing the impedance analogy, the sound pressure p and volume velocity v at locations 1(upstream end) and 2 (downstream end) in Figure 3 (x=0 and x=L, in order) can be stated by:

$$P1=AP2+BV2 \tag{1}$$

$$V1=CP2+DV2 \tag{2}$$

Where A, B, C, and D are usually called the four-pole constants. They are frequency- dependent complex values manifesting the acoustical characteristics of the tube [8].
The four-pole constants for non-viscous medium are:

$$A=\exp(-jMk_cL)\cos K_cL \tag{3}$$

$$B=j(\rho c/S)\exp(-jMkcL)\sin KcL \tag{4}$$

$$C=j(S/\rho c)\exp(-jMkcL)\sin KcL \tag{5}$$

$$D=\exp(-jMkcL)\cos KcL \tag{6}$$

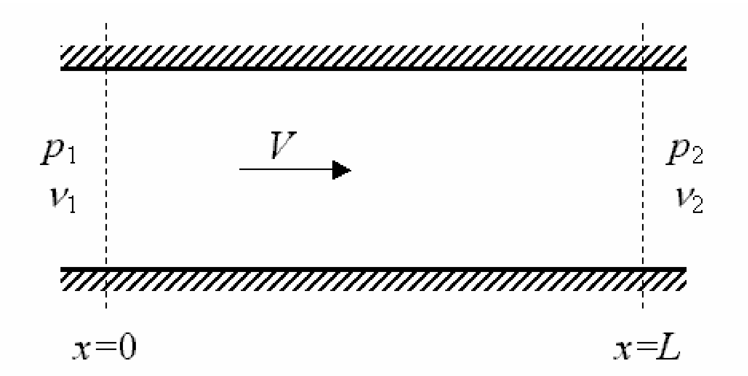

Figure 3. Plane wave propagation in a rigid straight pipe transporting a turbulent incompressible mean flow [8].

Where M=V/c is the Mach number of mean flow which is less than 0.2, c is the sound speed (m/s), is the thermally conductive wavenumber(rad/m) ($K_c=K/1-M^2$)), k is the acoustic wavenumber (rad/m)), ($k=\omega/c$), ω is the angular frequency (rad/s), ρ is the fluid density (kg/m3), and j is the square root of -1. In Eqs. (3) to (6), by substituting the quantity of M=0 for stationary Medium.

The equations (1) and (2) can be written in the way of matrix form as:

$$q_2=T_1q_2 \tag{7}$$

Where $q_i=[P_iV_i]^T$ is a vector of thermally conductive state variables (i=1, 2) and

$$T_1== \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{8}$$

The regarded approach computes the TL of muffler by using transfer matrix approach. A linear acoustic 4 pole transfer matrix:

$$\begin{bmatrix} P_1(x) \\ V_1(x) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} P_2(x) \\ -V_2(x) \end{bmatrix} \quad (9)$$

$$P_1 = P_+\exp(-ik^1L_1)+P_-\exp(ik^1L_1) \quad (10)$$

$$V_1 = \frac{A_a}{\rho c}\{(P_+\exp(-ik^1L_1)-P_-\exp(ik^1L_1)\}$$

and

$$P_2 = P_+\exp(-ik^2L_2)+P_-\exp(ik^2L_2) \quad (11)$$

$$V_2 = \frac{A_b}{\rho c}\{(P_+\exp(-ik^2L_2)-P_-\exp(ik^2L_2)\}$$

2.3. Transmission Loss

The characterization of a muffling device used for noise control applications can be given in terms of the attenuation, insertion loss, transmission loss, and the noise reduction. Transmission loss is defined as follows:

$$TL = 10Log_{10}\frac{W_i}{W_t} \quad (12)$$

Where w_i, w_t denote incident and transmitted sound power of the acoustic wave present in the exhaust-duct system.

Also, in this paper depict the modelling of mufflers using AVL Boost software and discusses the ideas of the proper transformation of an Audi A6 muffler geometry to a linear acoustic calculation model as shown in figure 4.

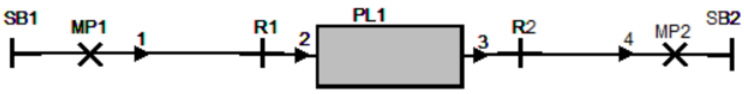

Figure 4. Muffler model scheme using 1D -AVL Boost

3. Results and Discussion

The calculation of transmission loss (TL) in decibel (dB) of such muffler over a wide frequency range from 0 to 2000 Hz is shown in Figure 5 and Figure 6. Figure 5 shows the TL for the original Audi A6 muffler.

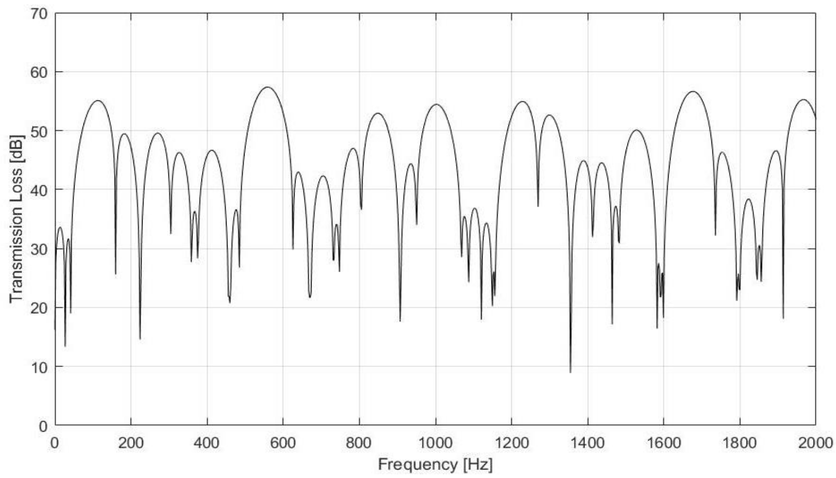

Figure 5 Transmission loss of a chamber with mesh plate at the middle; TMM results.

When the muffler size is reduced without changing the number of holes in inlet pipes and baffle position, the overall transmission loss increased from 55 dB to 65 dB. See figure 6.

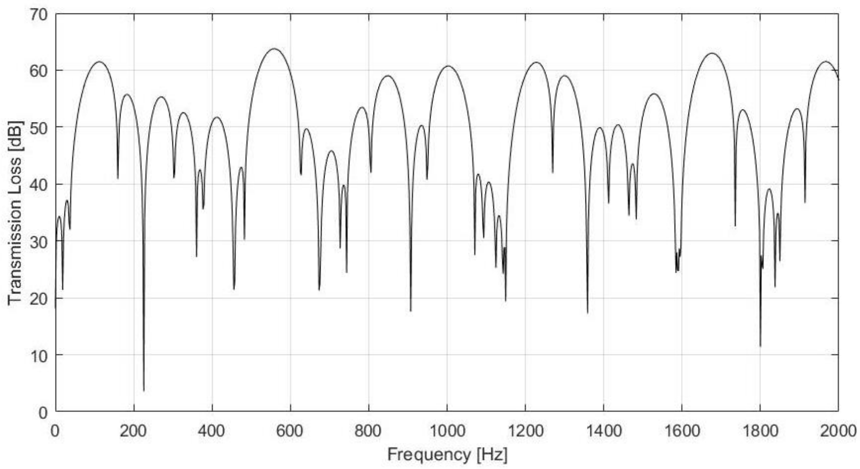

Figure 6 Transmission loss of a chamber with mesh plate at the middle, and reduction 15% of total volume of muffler; TMM results

Geometry		Numerical calculation	
Volume (v)	$501480mm^3$	TL of current muffler from TMM	55 dB
Inner diameter (D)	$60mm$	TL of modified muffler from TMM	65 dB
Outer diameter (d)	$65mm$	Frequency range (f)	0-2000 Hz
Porous diameter (D_p)	$2mm$	TL from 1D-Boost analysis	68 dB

Table 1. Data for the investigated muffler

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4. Conclusions

The MATLAB codes have been written for existing and down sized mufflers, these calculation results have been verified with CFD tools calculations from other literatures. Based on above analysis we can conclude below points:

- The reduction 15% of total volume of muffler provides considerably better TL values than the original size.
- When the muffler size is reduced without changing the number of holes in inlet pipes and baffle position, the transmission loss increased from 55 dB to 60 dB.
- The effect of existing mesh plate inside the chamber on transmission loss was slightly positive, replacing position of mesh plate doesn't have any real effect on acoustic pressure level, and transmission loss.
- Tuning the muffler could be done after replacing the mesh plate to porous joiner.

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